EFFICIENCY OF AN ELECTRON MULTIPLIER TUBE

BY

F. COSTAGLIOLA

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Report by

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Introduction.

The electron multiplier is a device which utilizes the phenomena of secondary emission for multiplying a single electron into an avalanche of electrons. Through a suitable amplifier and scaler it gives results similar to the Geiger Mueller counter. Since no gas is required, it operates in a vacuum, no window need be interposed between the source and the multiplier when the instrument is used in conjunction with a Beta ray spectrometer. Furthermore, secondary emitters are most efficient for incident electrons having energies on the order of 400 to 800 electron volts. Therefore, the electron multiplier should be particularly useful for detection of extremely low energy electrons. The writer proposes to use it for investigation of the low energy end of Beta ray spectra with W. M. Klee and M. U. Moore who are working on the source problem and the spectrometer problem.

Unlike the Geiger counter which is considered to have nearly 100% efficiency for all electrons that have sufficient energy to penetrate the window, it is not expected that the electron multiplier will be equally as efficient at all energies. It is necessary to find out what this efficiency is as a function of energy primarily.

With the aid of an electron gun as source of electrons, it is planned to measure the input current utilizing the complete electron multiplier assembly as a Faraday Cage. Then with the electron multiplier in its conventional role, it is

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planned to obtain the counting rate for comparison. In order to obtain any degree of accuracy it is necessary to employ a very sensitive current measuring device and a very fast counting circuit.

It was deemed a possibility that an appreciable percentage of the incident electrons might escape back out of the cage. This would seriously impair the accuracy of input current measurements. It was therefore necessary to investigate electron scattering theory and experimental work in order to make some estimate of the number of electrons lost.

Investigations into the characteristics of electron multipliers, the design of sensitive current measuring circuits, the scattering of electrons at various energies, the phenomena of secondary emission, and the design of electron guns, indicate that the method proposed for determining the efficiency of the electron multiplier is feasible. However, the results will probably not be as accurate for energies below about twenty kilovolts as for energies above twenty kilovolts.

This paper is a summary of the investigations made and the conclusions drawn from those investigations.

Secondary Emission.

The actual mechanics of secondary emission is not very well understood. The operation of the electron multiplier is based on the fact that some materials, under certain conditions, emit as many as ten secondaries for a single incident electron. For most of these materials the maximum number of secondaries is emitted for incident electrons ranging in energy from 400 to 800 electron volts.

As may be seen from Fig. 1, taken from Owen-Harries comprehensive article (H-3) on secondary emission, the kinetic energy of the secondaries is usually either very small or else very close to the energy of the incident electrons. The particular curve is produced by 155 volt primaries, but the general shape holds between 20 and 10,000 volts for most pure metals and some alloys. Peak A is produced by elastically reflected electrons while the remainder of the curve represents the true secondaries. The percentage of true secondaries to reflected secondaries increases steadily with increasing energy to about 1000 volts after which it falls off again. Fig. 2, also from Owen-Harries (H-3) shows how different materials compare in the number of secondaries (total including reflected and true secondaries) emitted for various energies of incident electrons. Fig. 3, taken from Allen (A-7, A-8), is the same type of curve for Beryllium Copper alloy. These graphs combined with Fig. 4 from Trump and Van de Graaff (T-1) indicate that secondary emission is not significant for most materials for incident electrons of about two or three thousand volts and beyond. That is, the multiplication factor drops to one or less.

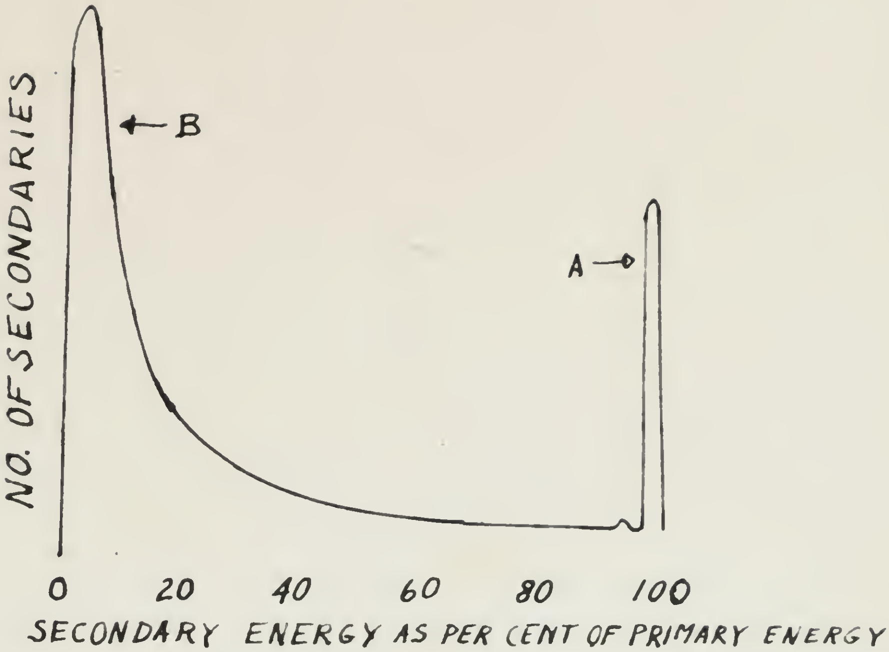


FIG. 1 ENERGY DISTRIBUTION OF SECONDARY ELECTRONS

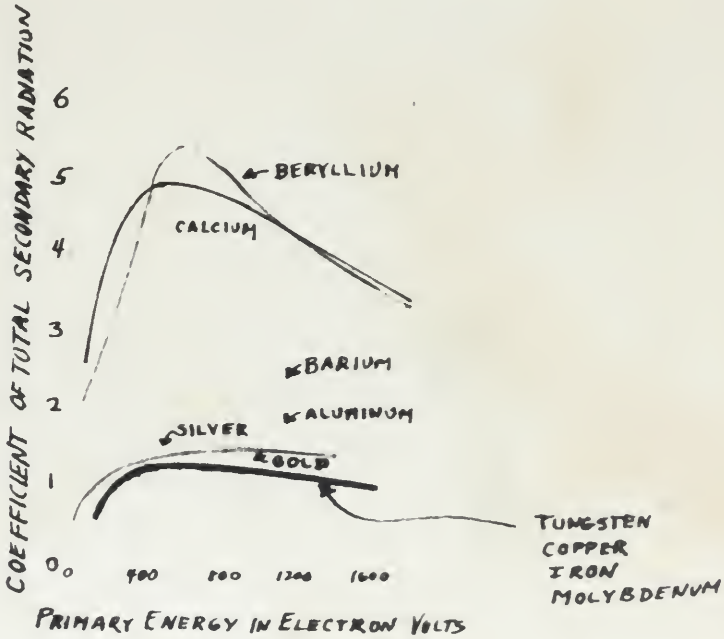


FIG. 2 COEFFICIENT OF SECONDARY RADIATION FOR VARIOUS SUBSTANCES.

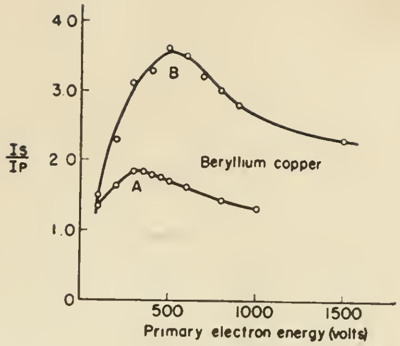


FIG 3. MULTIPLICATION OF BE CU ALLOY (A) UNACTIVATED (B) ACTIVATED

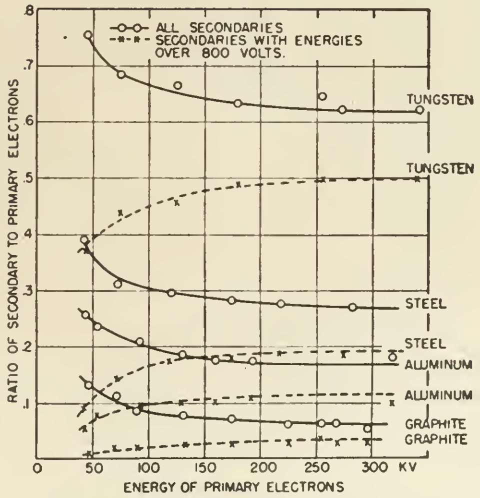


FIG. 4. Secondary emission of electrons by electrons with energies up to 340 kv.

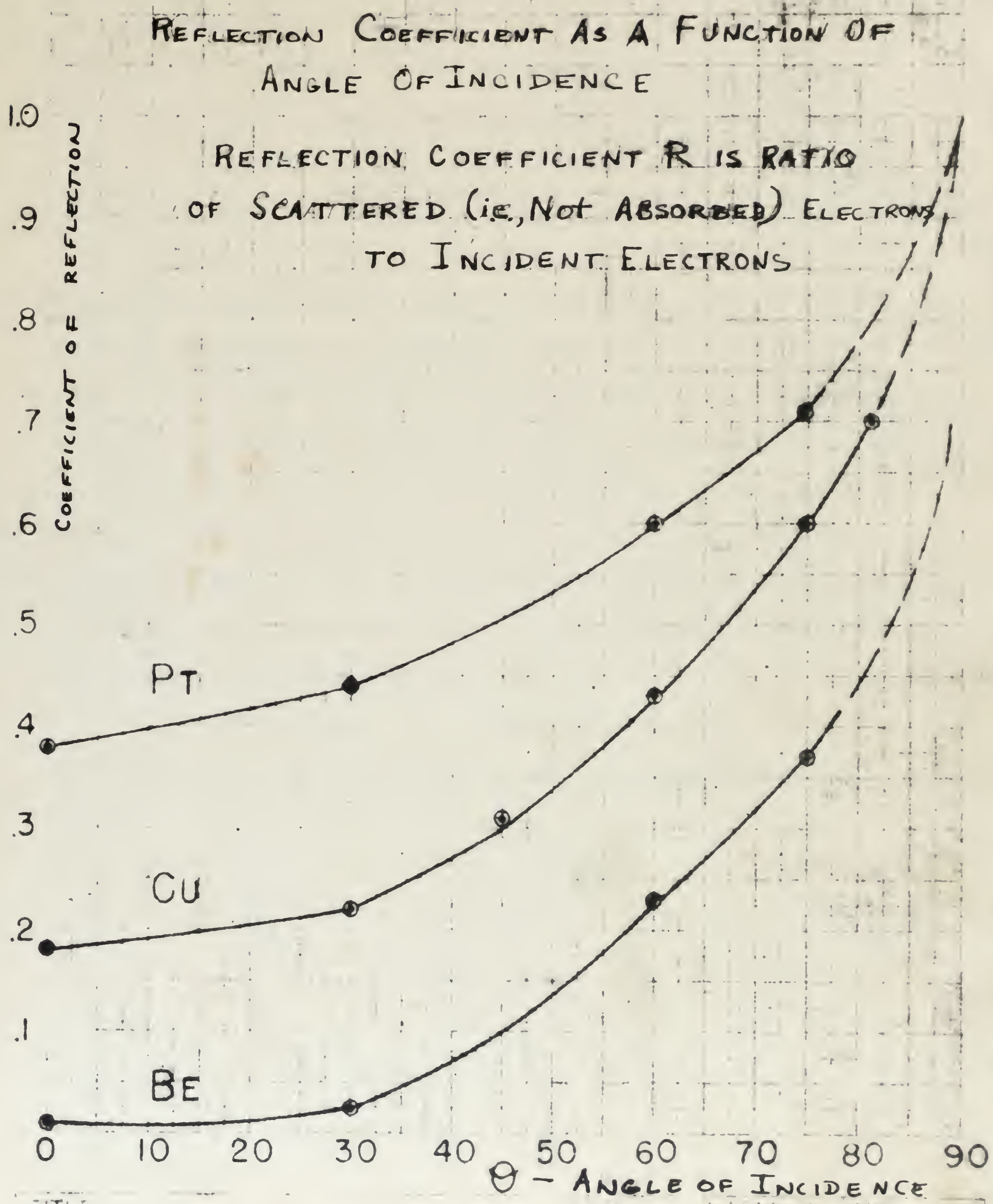
At this point, however, it should be noted that the apparatus which Trump and Van de Graaff used measured the secondaries for primaries striking at an angle of incidence equal to zero. Although up to several hundred volts energy the multiplication factor appears to be independent of the angle of incidence, at higher energies this does not hold true. At an angle of incidence of zero the least number of secondaries is obtained per primary and at ninety degree incidence the maximum. As an extreme example see Fig. 5 from Woodward's (W-1) work with 1.88 MEV electrons on various materials.

It is apparent that in working with electrons at energies below two kilovolts it would be very desirable to keep away from materials that are good secondary emitters for source chambers, for channel walls of the spectrometer, for baffles and so forth.

In accord with the usual perversity of nature, secondary emission is a nuisance when not wanted but difficult to obtain when desired. A process of activation is required in order to obtain the optimum multiplications shown in Figs. 2 and 3.

Zworykin, a pioneer in the electron multiplier field, found (Z-3) that AgMg alloy has many desirable characteristics as a secondary emitter. He found that he could, by one method of treatment, obtain an extremely high rate of secondary emission, but it would last only a few hours, tapering off rapidly. With another type of treatment he would get a lower initial multiplication factor but the factor was constant for more than a thousand hours of use.

Dr. Allen who had used Beryllium plated dynodes in his multipliers for several years changed over to BeCu alloy



REFLECTION COEFFICIENT AS A FUNCTION OF ANGLE OF INCIDENCE

REFLECTION COEFFICIENT R IS RATIO OF SCATTERED (ie., Not ABSORBED) ELECTRONS TO INCIDENT ELECTRONS

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FIG 5

(2% Be by weight) after the investigations of Gilles (G-3) and Mathes (M-17) indicated that a multiplication factor of ten was possible with it.
However, Allen learned by experimenting with various heat treatments that a multiplication greater than four was very difficult to arrive at, the maximum being 5.5 with a slightly oxidized sample (A-7). Allen used vacuum firing. Dare and Rowan (D-1) used vacuum firing unsuccessfully on their Allen tubes but found hydrogen firing satisfactory. W. E. Wright who has constructed two modified Allen tubes at MIT for gamma ray detection has also used hydrogen firing to his satisfaction. T. M. Hahn, Jr. has built several modified Allen tubes for ion detection in the Molecular Beam Lab. at MIT and has obtained satisfactory results with vacuum firing. Apparently, though, no one has been able to obtain a multiplication average per stage of an assembled multiplier much greater than three using either method of firing.

All workers agree that the multiplication factor drops steadily with time of exposure to the atmosphere after activation.

The Electron Multiplier.

Back in 1919 Slepian patented a "hot cathode tube" that employed secondary emission for amplification purposes. It used magnetic fields for channeling the electrons. But it was not until the mid-thirties that the first multipliers approaching practicability, the "L" and "T" types of Zworykin (Z-1, Z-2), were built.

It was soon found that electrostatic fields were superior to magnetic fields for channeling the electrons from one stage to the next. Zworykin concentrated on this type and eventually evolved what is now the 931A Phototube. It is an electron multiplier in which the first stage is photosensitive, the electrons which the first stage emits being multiplied by a series of stages of secondary emitting material. The stages or dynodes are shaped to get the best focusing effect, while the potential between them is such that the secondaries emitted are accelerated to the energy that gives the greatest multiplication factor.

More recently Allen (A-1,2,3,4,5,7,8) working in this field found that Beryllium was not only a good emitter but that it had a high work function making it insensitive to light photons. Even more important it had negligible dark current, a serious disadvantage of the 931A. Beryllium is sensitive to X-rays, Gamma rays and to charged particles.

Allen designed an electron multiplier with a series of stages of Be. To find the most suitable shape and arrangement for his dynodes, he used the mechanical model analogy (see S-4); that is, he built an experimental set of dynodes so that when placed on end the drop in height between succes-

sive dynodes was proportional to the potential to be placed between them. Then a rubber sheet was stretched over this assembly. By observing how a small steel ball reacted in travelling along the membrane and then changing the orientation and/or the shape of the dynodes to get better performance he arrived at the design used in his multipliers. As previously mentioned he later substituted BeCu for Be. This seems to have all the advantages of Be and in addition is available commercially in a suitable form. A version of this Allen tube is to be used by the writer in his research.

Dare and Rowen (D-1) were the first to build this type at MIT. The dynodes which they used were made from dies shaped to Allen's specifications. The dies are available in the NS and EL machine shop. The edges of the dynode sheets were crimped over nichrome wire which acted both as conductor and support. Nichrome wire is hard to solder, however, and Hahn has been using Nickel wire to much better advantage.

Allen used lavite as a support for the orientation and spacing of the dynodes with respect to each other. Lavite has the advantage that as obtained, it is soft, easily drilled and shaped. It becomes hard after proper baking procedure. The dynodes have to be activated separately if hydrogen firing is used. If refiring with the hydrogen method becomes necessary, the assembly must be dismantled or the lavite will lose its insulation properties. Dare and Rowen turned to Micalex to avoid this difficulty, but it has the disadvantage that it is very hard and is difficult to drill, etc. Both Hahn and Wright are experimenting with mica as a second alternative.

The dynode assembly is mounted on four of the Kovar outlet leads which act as supporting pillars from the base plate.

A great deal of difficulty has been experienced in sealing the base plate. The leads through the base plate are at potentials which run from zero to 4500 volts or more. In the past, Kovar seals made by a glassblower in the IRE Lab at MIT have been used; in the soldering process, however, the seals have often broken because of the difference in expansion coefficients of the glass and the Kovar eyelet. A good deal of progress was made in improving the design to eliminate this weakness. An even better solution seems to be to use a commercial glass seal such as that manufactured by Stupakoff, available in the NS and EL stockroom. In the Dare and Rowen tubes the seals were soldered to the base plates on the inner or vacuum side; it would appear better to solder them from the outside, thus taking advantage of the pressure difference to aid in the sealing.

Dare and Rowen used a one-half inch tube with a ninety degree bend in it for connecting the multiplier to the vacuum pump. Dr. Clark of the Synchrotron Laboratory suggested that a one inch tube with no bend would give much better results. The base plate has been redesigned with this in mind as well as the idea of using the tube as support when the instrument is mounted outside the vacuum tank being built by Klee. Adjustments were also made so that it will be relatively easy to install in, and to remove from, the vacuum tank.

In order to provide the proper voltage to each dynode it is necessary that a voltage divider be used across the power supply. Dare and Rowen used a three megohm resistor between stages by-passed with a .03 mfd condenser to eliminate 60 cycle hum and so forth. Fig. 6 shows Allen's arrangement. Hahn has been using ten megohm resistors between stages. In addition, Hahn has eliminated most of the leads through the base plate and reduced corona difficulties by installing his resistors inside the vacuum. He dipped them in acetone to remove the paint prior to installing and he reports no difficulty in obtaining a good vacuum. Because the writer has to short all his dynodes together when using the multiplier as a Faraday Cage, it will not be possible to eliminate the leads through the base plate but it would be feasible to eliminate the leads from the base plate on out, a serious source of corona trouble in the past.

As used by Dare and Rowen the multiplier had a cylindrical "can" as a housing with a window located in the appropriate position for the incident particles to penetrate to the first dynode. This is the manner in which the writer plans to use the multiplier in preliminary tests. However, when used in the vacuum tank being constructed by Klee, the window will be removed and the base installed vacuum pipe will be blanked off.

Dare and Rowen used a positively grounded power supply. Therefore, the first stage of the electron multiplier had to be at -4500 volts while the output dynode was at ground potential. For safety's sake, if no other, the "can", base plate, etc. had to be at ground potential. This means that an in-

cident electron would be subjected to a retarding field of 4500 volts. Therefore, the minimum energy of incident electrons which would register would be 4500 volts. Since we are particularly interested in the low energy Beta rays, this would be a serious handicap. Hence it was decided to employ a negatively grounded power supply.

There appear to be several other advantages to using a negatively grounded power supply for the Allen Tube when using it as a Beta ray detector.

(1) Lower limit of energy of Beta particles detected practically zero.

(2) Since the "can" will be at the same potential as the first stage, background due to positive ions formed within the electron multiplier should be negligible.

(3) Pulses should be larger and efficiency greater. From the construction of the Allen tube it seems quite conceivable that with the previous arrangement the potential gradient between the first stage and the "can" near the window was greater than the potential gradient between the first and second stages. In such an event many of the secondaries produced in the first stage would fail to reach the second stage, thus greatly reducing both the gain and the efficiency of the multiplier.

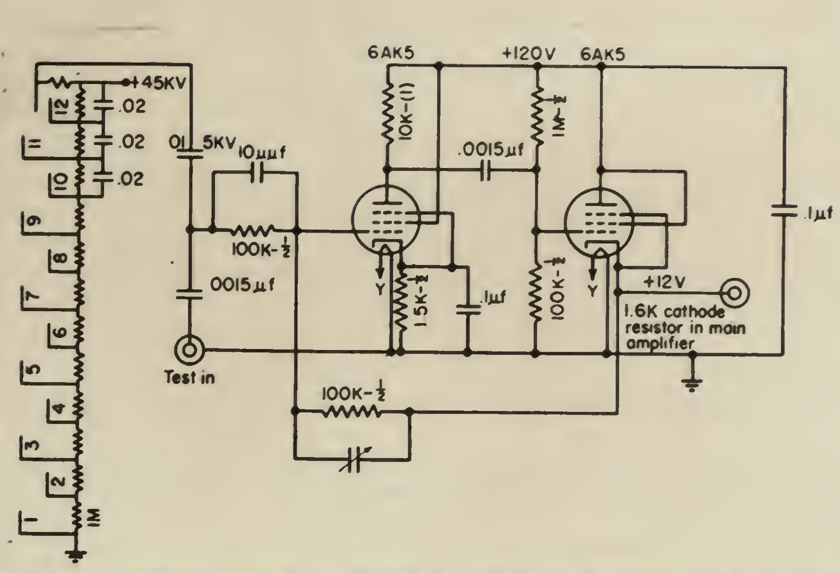
(4) Beta rays would lose no energy in entering the multiplier.

The one disadvantage in using negative grounding is that since the output is at a high potential the signal has to be relayed through a high voltage coupling condenser. Since the input capacity of most amplifiers is on the order of ten micromicrofarads, a loss of only nine percent in gain will result if we use a 100 micromicrofarad condenser for coupling. With an input grid resistance of 10K the resolving time will be on the order of a microsecond which should be sufficient for the present requirements.

Measuring Small Currents.

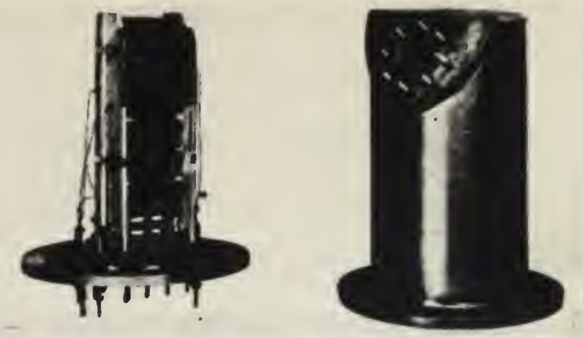
The amplifier built by Dare and Rosen (D-1) for use with the electron multiplier was designed to handle better than 10^6 counts per second. The writer intends to use the same amplifier. The resolving time of the multiplier itself is on the order of 10^{-9} seconds. Incidentally, this short resolving time is another of the electron multiplier's advantages. The resolving time of the input stage of a conventional scaling circuit is on the order of three to five microseconds (E-5). A safe estimate of resolving time from the multiplier through the coupling, preamplifier, amplifier, and into the scalar appears to be 10^{-5} seconds. But the real limit on maximum number of counts is the relay used to actuate the mechanical counter in the scaling circuit, as well as the number of flip flop stages in the scaling circuit. Since the relay limit is about thirty counts per minute a 4096 scaler will have a resolving time of about 500 microseconds or permit a maximum counting rate of 2000 per second which corresponds to a current of 3.2×10^{-16} amperes. With this scaler it is expected that the pulses to the register will be nearly evenly spaced. Hahn uses a "Cenco" register which is capable of recording about 20 cycles per second. With such an arrangement, counts corresponding to about 1×10^{-14} amperes could be registered.

For determining the efficiency, two types of instruments are capable of measuring currents this small, the electrometer and an electronic measuring circuit using an FP-54 (M-9). The DuBridge balanced circuit using two FP-54s is



Schematic diagram of a method of coupling the multiplier tube to the pre-amplifier

FIG. 6



Electrode system and metal tube shell of a 13-stage tube

FIG. 7

the most sensitive of the electronic circuits (D-3,7;N-1,2;P-4) and is considerably more rugged than an electrometer. One of the galvanometers available in the Synchrotron Laboratory was found to be satisfactory if used in conjunction with this circuit along with a 100,000 ohm Ayrton Shunt, also available.

Fig. 8 is a diagram of the circuit which the writer intends to employ. The calculations may be found in Appendix A.

The limit of sensitivity for this type of circuit, when using the rate of change of charge method, is the fluctuation in grid current. On the basis of manufacturers' claims for the tube, this fluctuation is 10^{-17} amperes. A current of $3.2x10^{-16}$ amperes would be measurable to within 3%, a current of $3x10^{-14}$ amperes to within .03%.

Still greater accuracy would be possible with a split FP-54 (L-5). It uses a single cathode for what amounts to two FP-54s in a single envelope. This, when employed in a suitable bridge circuit, eliminates the variations due to the fluctuations in filament emission, which is one of the causes for the present limit in sensitivity. However, this tube is not available commercially.

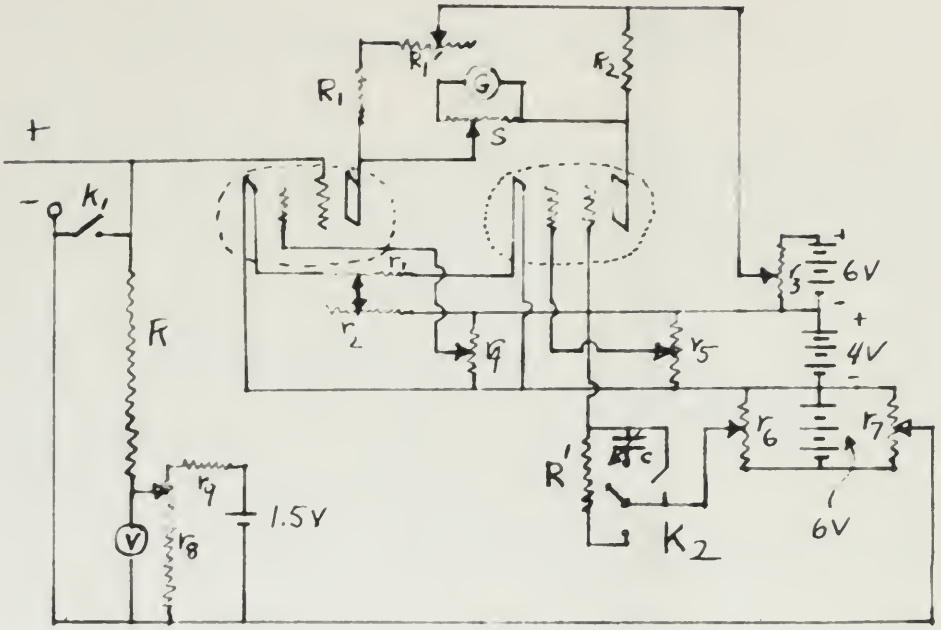
It is planned to enclose the entire DuBridge circuit in a practically airtight metal case to eliminate stray electric and magnetic field effects, as well as to reduce the effects of atmospheric changes on the input resistors and the leakage over the tube envelope's surfaces. Care will have to be used in assembling the circuit not to touch the input resistors

or the glass envelope with the bare hands. The circuit and galvenometer will have to be mounted with respect to the floor so that microphonics will be held to a minimum.

Fig. 8

D. C Amplifier (FP-54 Bridge type)

From DuBridge (D-7)



$R = 10^{11}$ ohms
$R' = 10^{11}$ ohms
$R_1 = 5000$
$R_2 = 10{,}000$
$R_1' = 10{,}000$ ohm resist box
$r_1 = 2$ ohm rheostat
$r_2 = 20$ ohm rheostat
$r_3 - r_8 = 400$ ohm pots
$r_9 = 1000$ ohm

K_1, K_2 } Electrometer keys

V = Millivoltmeter
S = 100,000 ohm Ayrton shunt
C_1 = 15 uuf Air condenser

G = Galvanometer
2.3×10^{-10} amps/mm

Electron Scattering.

Electron scattering enters the problem of determining the multiplier efficiency because in using the electron multiplier as a Faraday Cage, if some of the electrons should escape back out the opening, a true measure of the input current will not be obtained. Hence, it becomes necessary to know what percentage of the electrons are lost at the various energies from 0 to 100 kilovolts.

Electron scattering may be classified into four divisions (E-4):

1. (1) Elastic scattering by atomic electrons, particularly pronounced for very soft Beta rays.
2. (2) Elastic scattering by atomic nuclei also pronounced for soft Beta rays.
3. (3) Inelastic collisions with electrons for Beta rays of intermediate energy.
4. (4) Inelastic collisions of swift electrons with atomic nuclei.

The scattering formula of Mott (M-10,11,12,13) see Appendix B expresses the relationship between scattered electrons and incident electrons for very thin foils (single scattering) and for fast electrons. The formula has been found satisfactory experimentally for relatively small angles of deflection (angle between direction of incident electron and its direction of departure) by the work of Van de Graaff et al (V-1) and Buechner et al (B-6). The formula does not hold unless Wentzel's criterion is satisfied (M-10, S-12).

Wentzel's criterion determines the boundary between single scattering and multiple scattering.

Multiple scattering occurs most at small angles of deflection and least at large angles of deflection. Goudsmit and Saunderson (G-S) see Appendix C and E. J. Williams (W-7,8) have developed expressions for the multiple scattering of electrons in thin targets. Both formulas have been found to be in good agreement with experiment by Kulchitsky and Laytshev (K-5). These two formulas are not as explicit as the Mott formula. The criterion for determining the accuracy of the multiple scattering formulae is to compare max from the formula and the observed max where max is the angle corresponding to the most probable value of sin and is a measure for the width of the Gaussian curve sin is the direction which the electron assumes after having been scattered.

Fig. 9 shows what happens when the conditions found at the entrance window are substituted in the Mott formula. Although the results appear startling for the lowest energies, it must be pointed out that the Mott formula was not intended for these low energies; further, the target is so thick that Wentzel's criterion is not satisfied even for the angle of deflection of 180°.

Fig. 10 demonstrates the results obtained with Goudsmit and Saunderson's formula for two different sets of conditions. Since the formula requires Legendre functions for the angle of deflection and the table available (S-7) went only to 90°, no results could be obtained in the 180° region in

which we are particularly interested.

The subject was discussed with Dr. J. F. Woodward. He pointed out that thick targets present a very complicated problem in electron scattering and as yet no satisfactory theoretical work exists on the subject. He has, however, done some experimental work in this field which has not yet been published and kindly made the graphs of Figs. 5, 11-15 available.

The specular effect Dr. Woodward observed is particularly interesting. In the electron multiplier the average angle of incidence in the first dynode is about 70°. Therefore, by far the greatest number of electrons will be reflected onto the next stage, at least for the case of 1.88 Mev electrons. From the appearance of the copper curve a small fraction will be reflected back at -70°.

There doesn't appear to be any experimental evidence for this specular effect in the region below 100KV nor any evidence against it, since the work has usually been done with thin foils and not with thick targets.

Schonland (S-13) investigated the region 0-100KV for the relative amounts of cathode rays absorbed, transmitted, and reflected for various thicknesses of a number of elements. For electrons of angle of incidence 0° there is an upper limit for the percentage of reflected (angle of deflection greater than 90°) electrons. It is reached when the target is thick enough to stop all electrons from going through. Fig. 16 is a comparison of some fo Schonland's data with that from Woodward in Fig. 15. Woodward used very thick

targets and went to much higher energies. This data does not include secondaries, since precautions were taken to prevent secondaries from entering into the measurements.

Based on this information the experimental means shown in Fig. 17 has been devised for measuring the number of electrons lost directly.

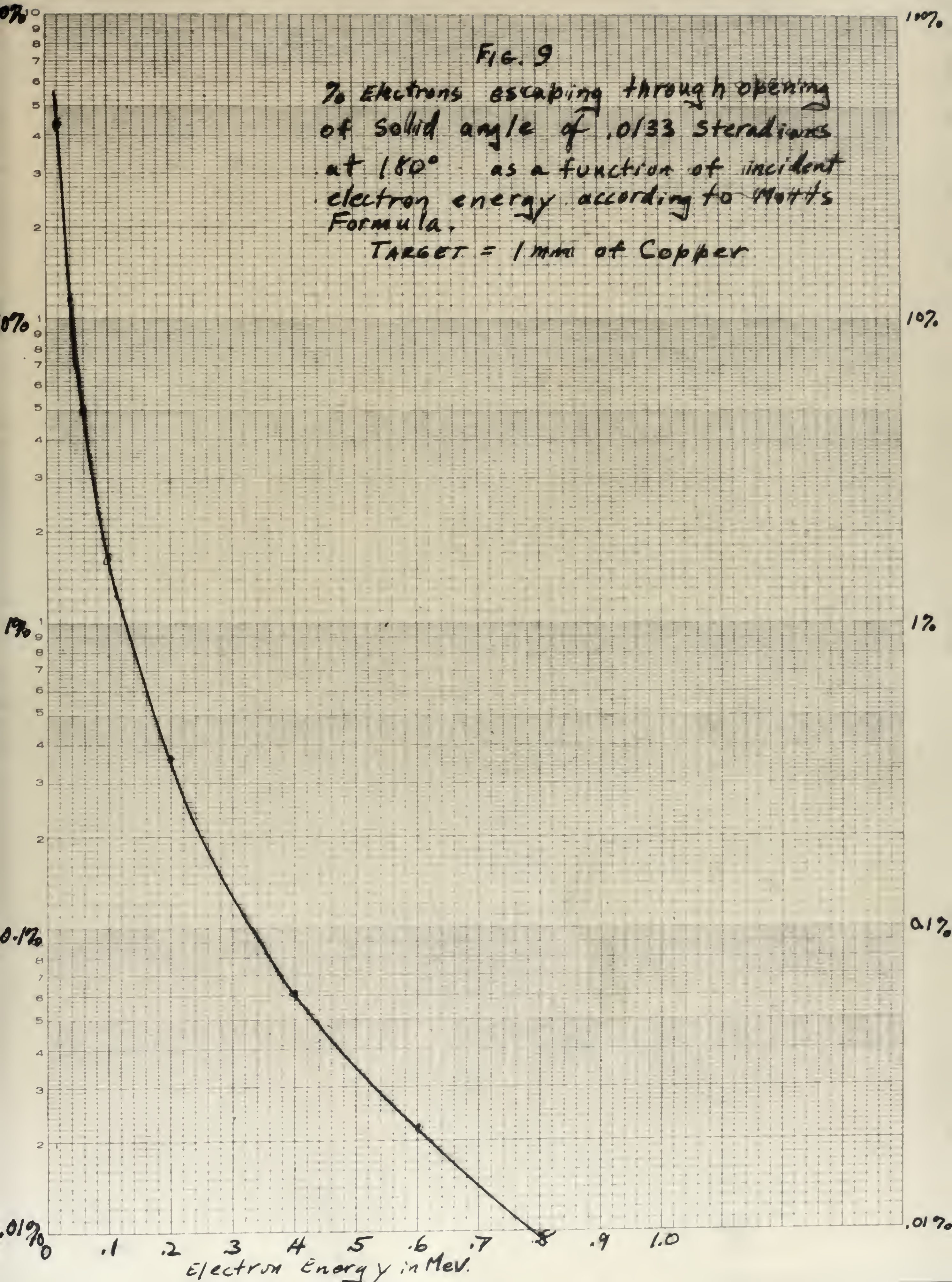


FIG. 9

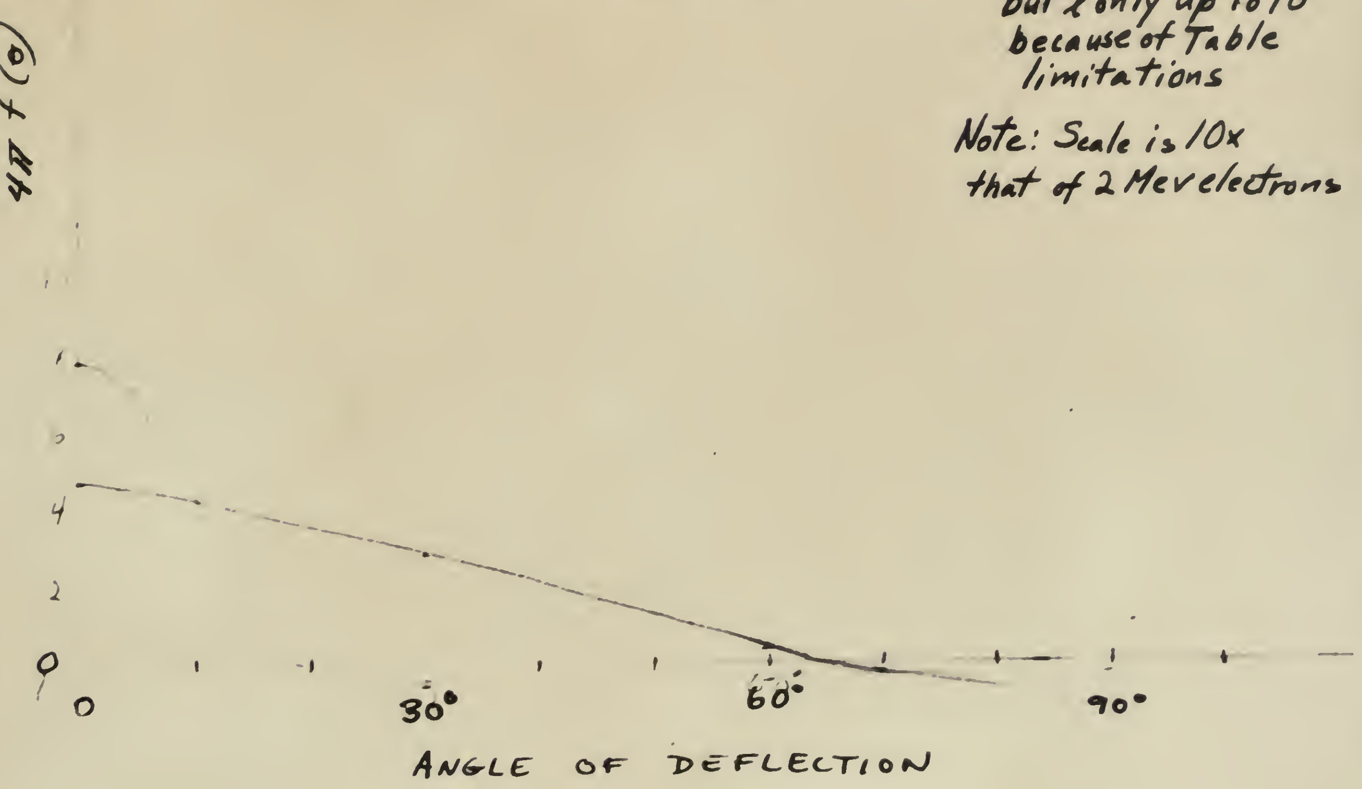
% Electrons escaping through opening of solid angle of .0133 Steradians at 180° as a function of incident electron energy according to Mott's Formula.

TARGET = 1 mm of Copper

FIG. 10

MULTIPLE SCATTERING OF ELECTRONS

Method of GOUDSMIT AND SAUNDERSON



2 Mev electrons
1mm Aluminum

1.25 Mev electrons
.025 mm Aluminum
but l only up to 10
because of Table
limitations

Note: Scale is 10x
that of 2 Mev electrons

$$f(\theta) = \frac{1}{4\pi} \sum (2\ell+1)\, G_\ell\, P_\ell(\cos\theta)$$

where $G_\ell = e^{-2\pi k^2 N t\, \ell(\ell+1)\left[\log \varepsilon - \left(\frac{1}{2}+\frac{1}{3}+\frac{1}{4} \cdots \frac{1}{\ell}\right)\right.}$

[see Appendix C]

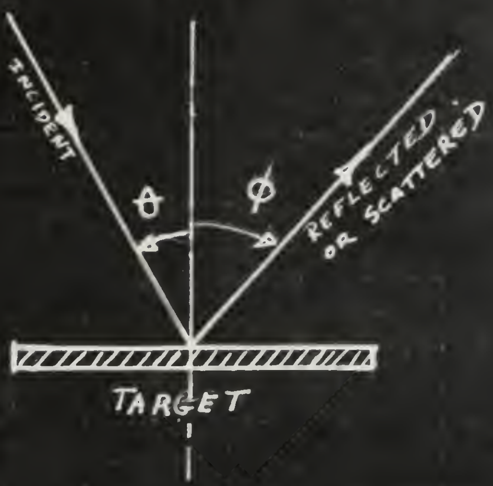


FIG. 11a DEFINITION OF θ AND OF φ AS USED IN WOODWARD'S WORK; (NOT THE SAME AS θ USED IN GOUDSMIT FORMULA).

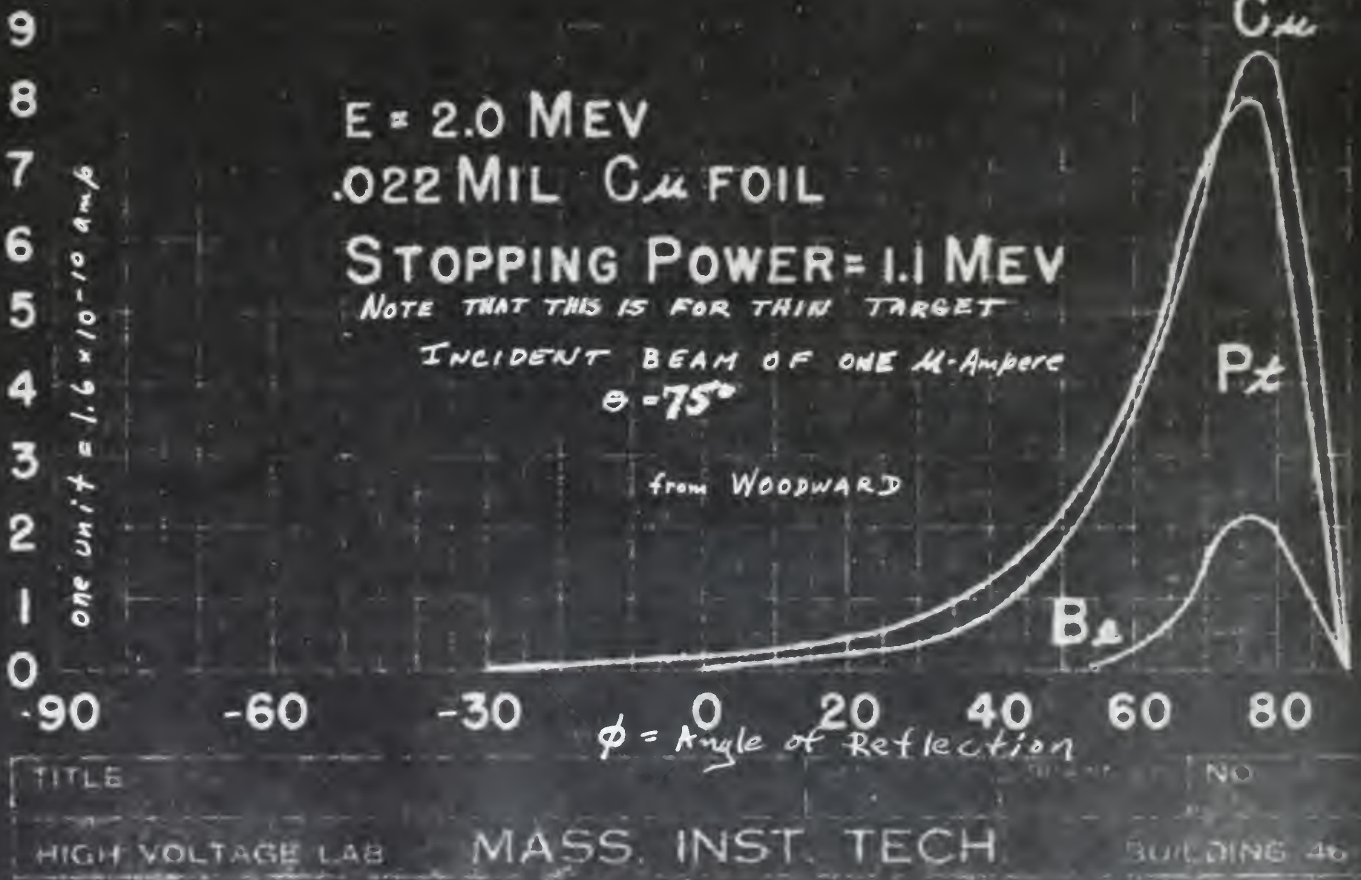


FIG 11 b

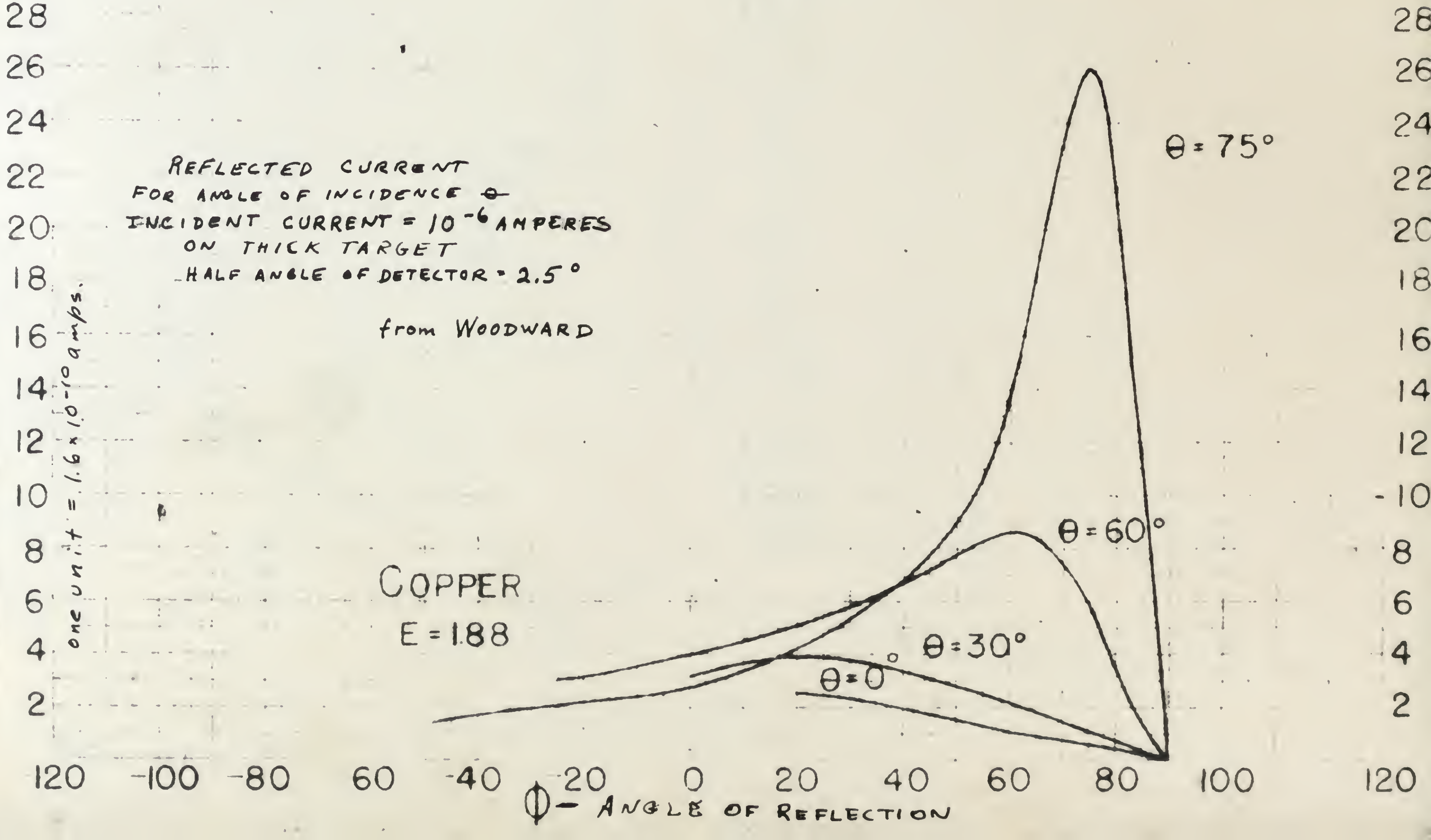


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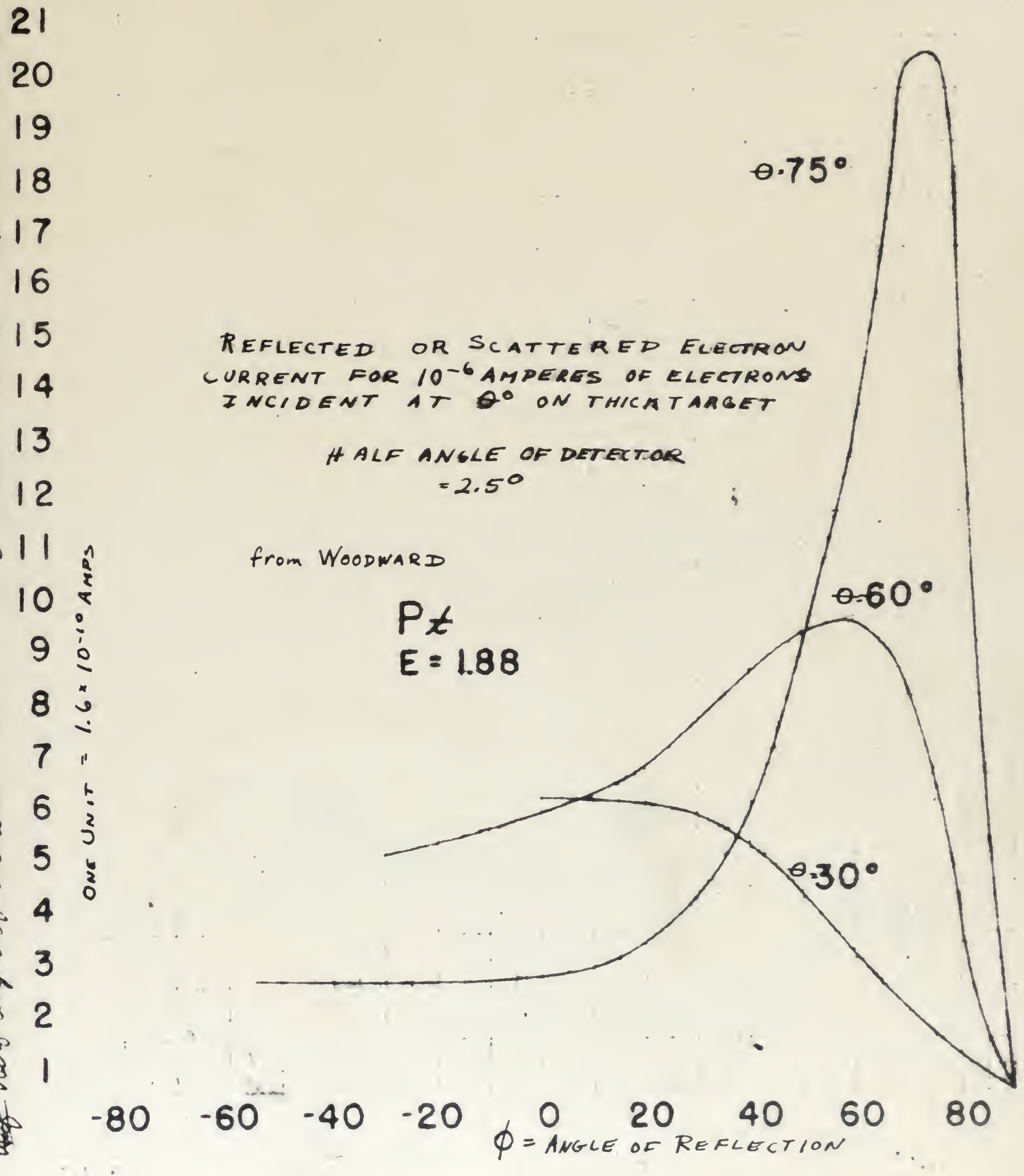
FIG 12



~~half~~ half angle of detection = 2.5°

Units on [illegible] 1 unit = $1.6 \cdot 10^{-10}$ amps / 1.4 amps of incident beam

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FIG 13

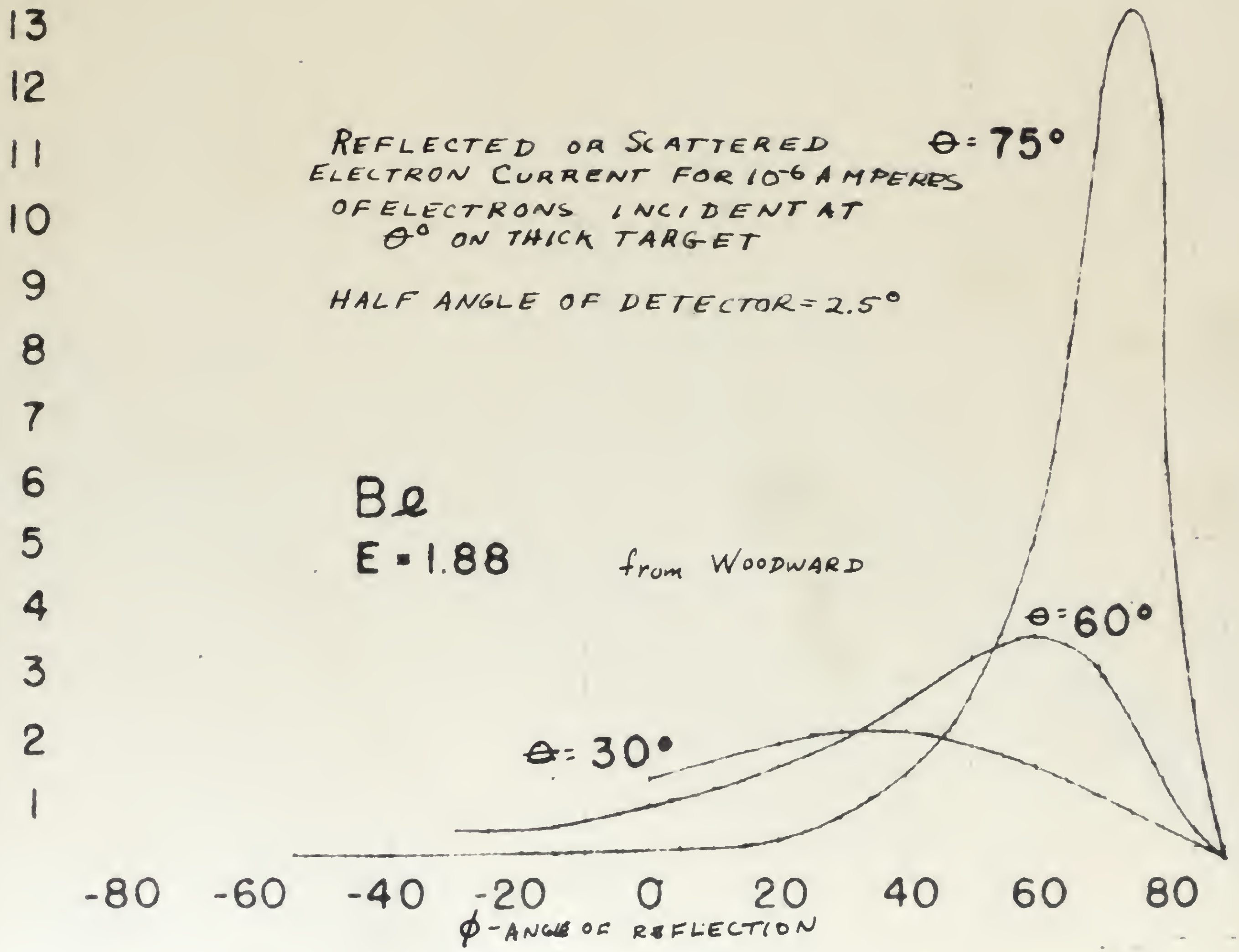

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FIG 14

TITLE

HIGH VOLTAGE LAB

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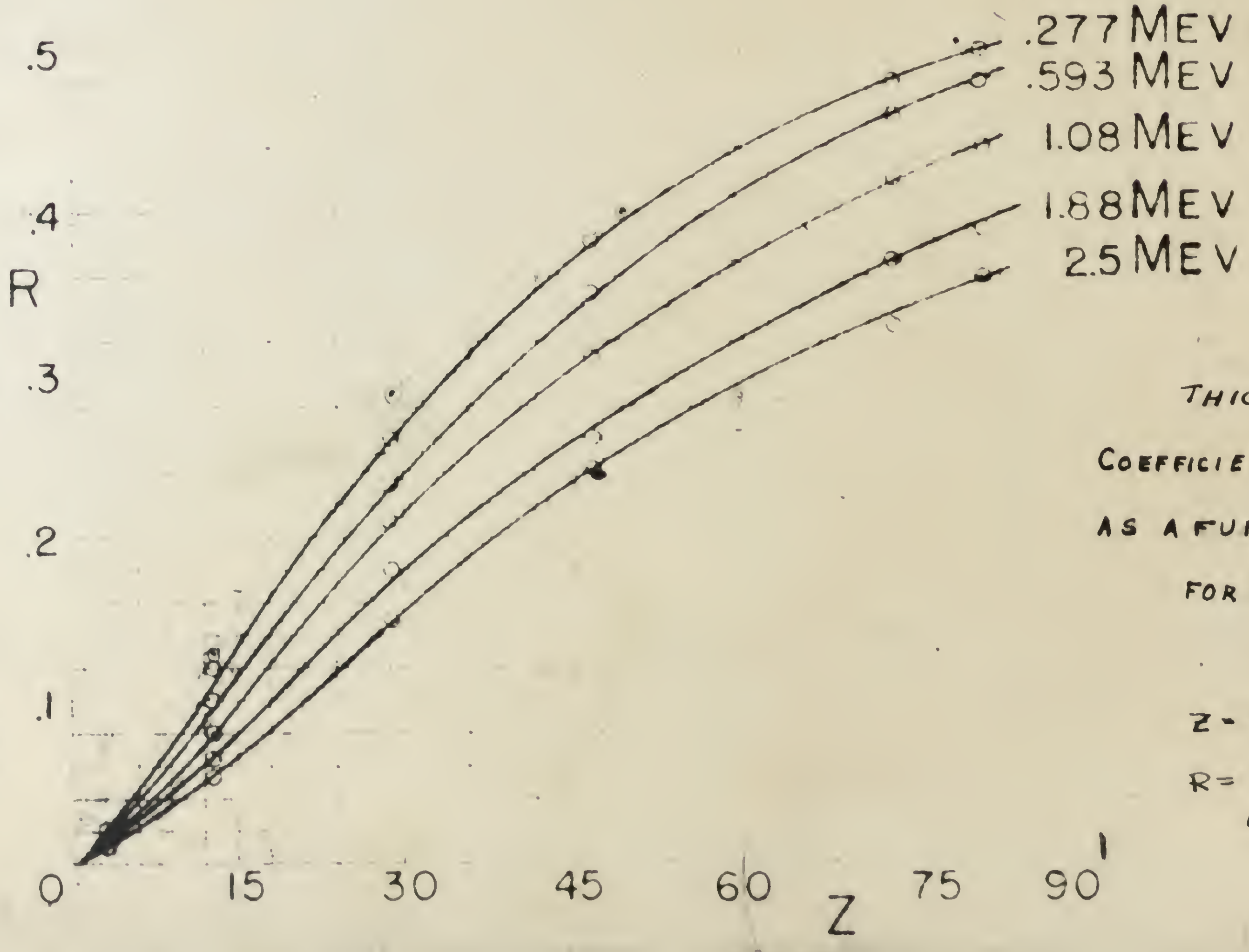
NO.



THICK TARGET

COEFFICIENT OF REFLECTION

AS A FUNCTION OF Z AND ENERGY

FOR ANGLE OF INCIDENCE = 0°

from WOODWARD

Z = ATOMIC NO.

R = RATIO OF SCATTERED TO INCIDENT ELECTRONS

FIG. 15

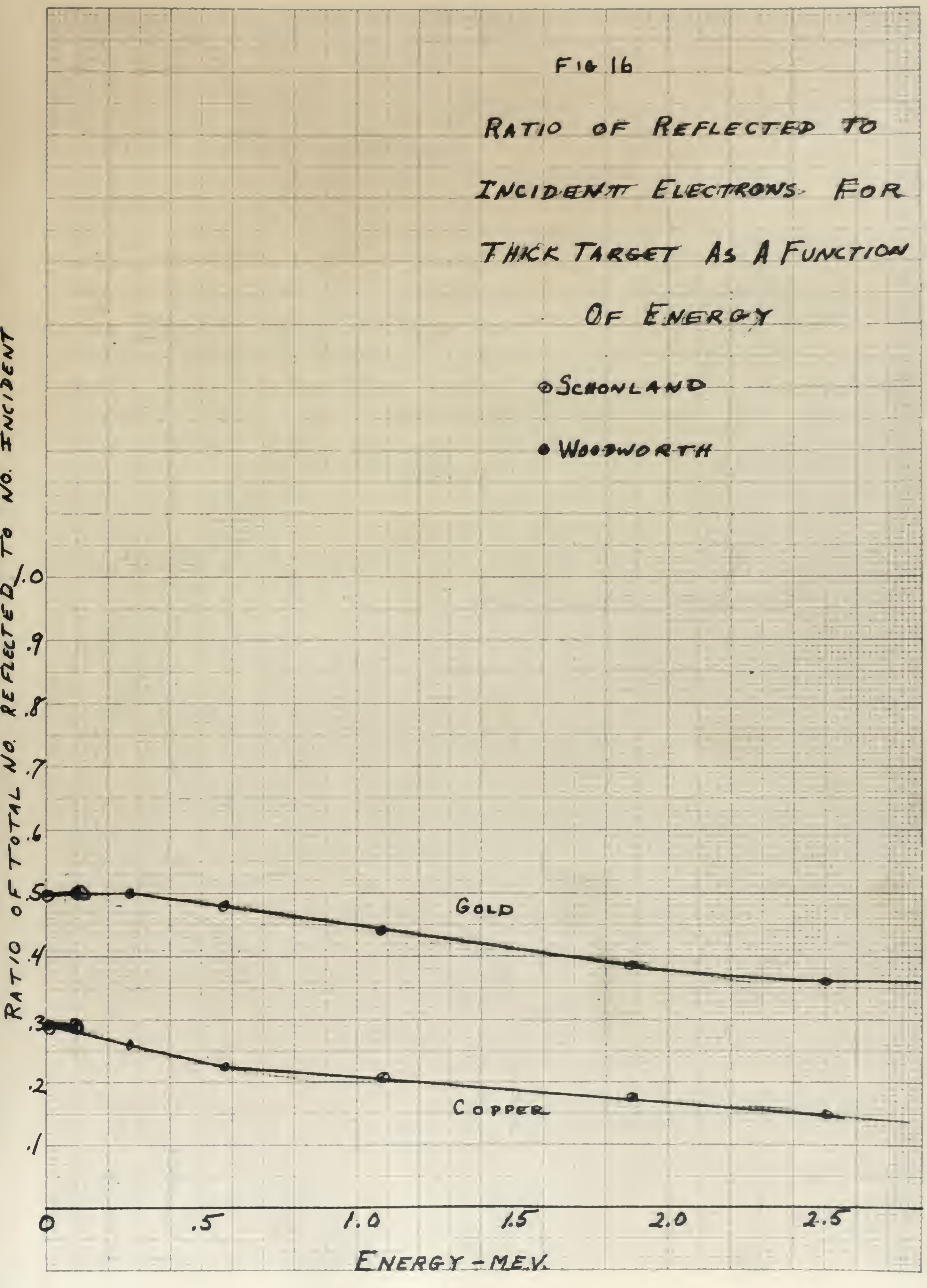
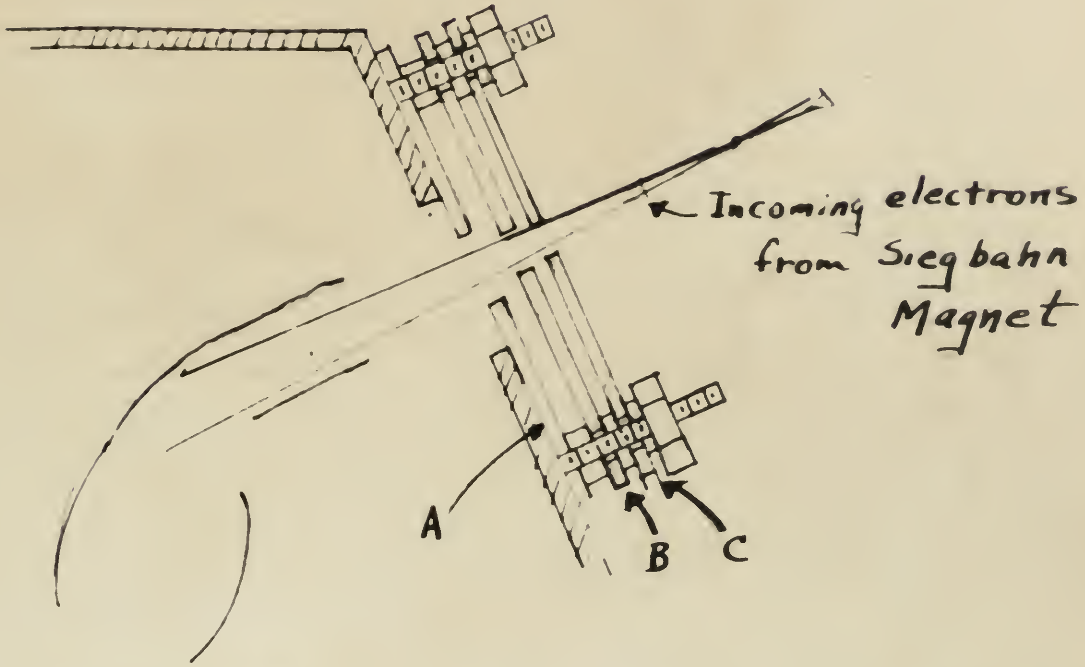


FIG 16

RATIO OF REFLECTED TO INCIDENT ELECTRONS FOR THICK TARGET AS A FUNCTION OF ENERGY

FIG 17

Device for Measuring Escaping Electrons



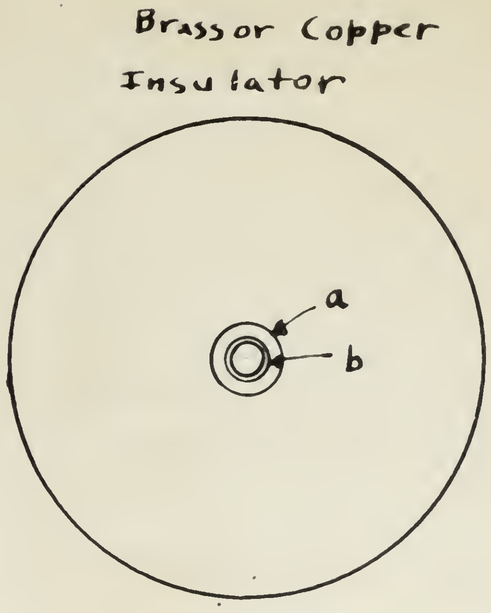


Plate A reduces the size of the "window" to reduce number of electrons escaping

Plate C protects B from stray electrons incident from the outside. Potential above ground to be sufficient to hold all secondaries.

Plate B is measuring plate. Its potential has to be sufficiently above ground to hold all secondaries.

Let a and b be the areas of the holes in A and B respectively i_B = measured current

$$\frac{i_B}{.29} \times \frac{a}{a-b} \approx \text{current lost out through plate A}$$

Factor taken from Fig. 16

FOR THIS MEASUREMENT INPUT CURRENT WILL HAVE TO BE HIGH.

Electron Gun.

Originally it was planned to use the electron gun adapted from a DuMont 5RP cathode ray tube by Anastassian and Seocenbaugh for their thesis. Modifications would have to be made in order to use it for our purposes. Since it focuses the electrons to a very small area, it would be necessary to sweep the beam over the dynode in order to prevent a type of fatigue observed by Allen (A-7). A preliminary design of sweep circuit has been prepared in the event that it should become necessary to revert to this electron gun for efficiency measurements. Defocusing is also feasible for this purpose.

It seems desirable when using any apparatus to test it as a unit, if possible, rather than piecemeal. Because of the bulk of most types of electron guns and the high voltages involved, however, it did not appear feasible to use one with the spectrometer under consideration. Dr. Getting called attention to the type of gun intended for use in the Synchrotron. It appears equally suitable for our purposes. A sketch of the gun proposed for use in the vacuum tank is shown in Fig. 18.

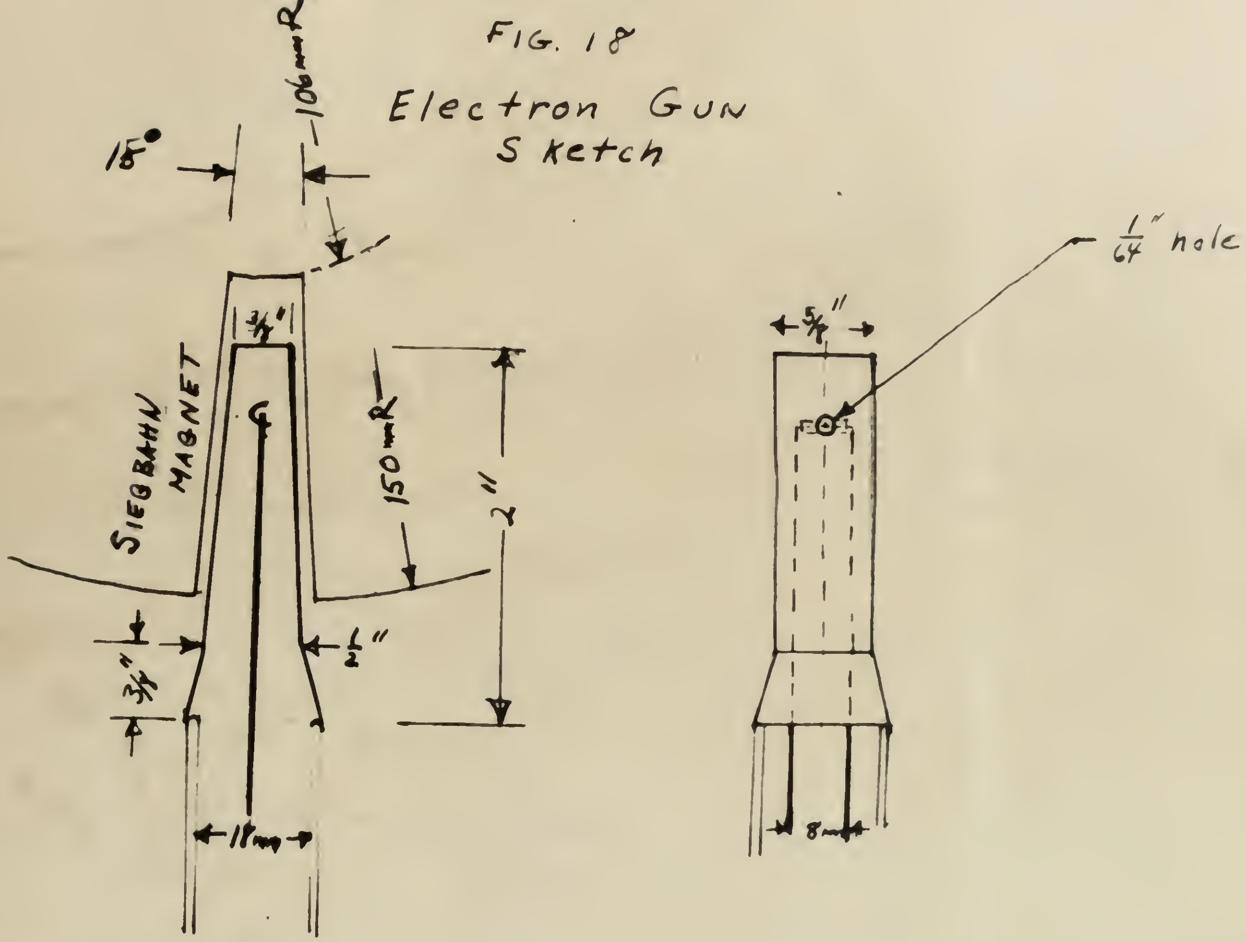
The orifice is small in order to hold down the number of electrons ejected from the gun. It is hoped that the energy of the electrons will be spread over a small band and that the Siegbahn magnet will have sufficient control and flexibility so that, if necessary, a portion of the band width may be cut out. Variation of filament current will give an

additional means of control.

The potential of the filament will be varied with respect to ground to provide the desired accelerating voltage.

FIG. 18

Electron Gun Sketch



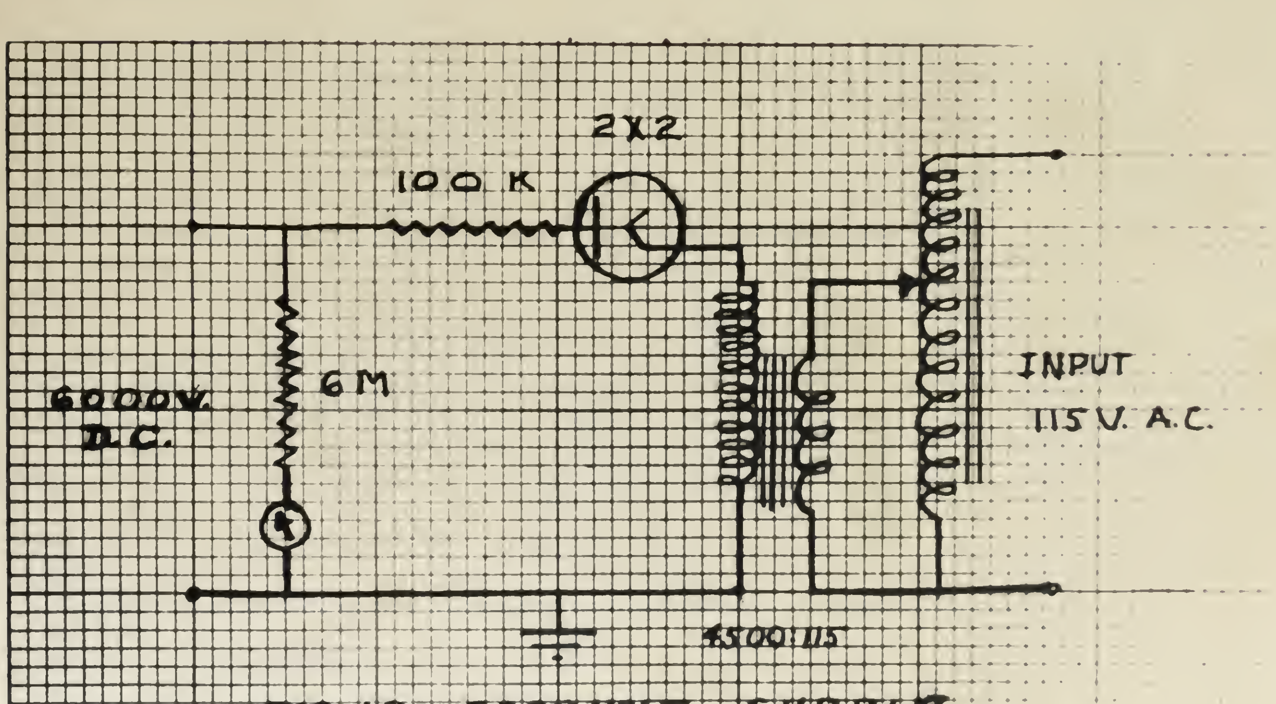


FIG 19 - 6000 VOLT SUPPLY

Power Supplies.

Two power supplies will be necessary, one for the electron multiplier itself and one for the electron gun. The writer has built a suitable supply for the electron multiplier, see Fig. 19. The design was provided in the main by Dr. Clark. It may be used either positively grounded or negatively grounded, the change being performed by merely exchanging two sets of terminals.

For the electron gun there is a Westinghouse X-ray unit available in the laboratory which will provide either positively or negatively grounded voltages from zero to seventy-five kilovolts. It may be possible to measure the efficiency at even higher voltages by using a 100 kilovolt pulse generator now being built in the Synchrotron Laboratory.

Conclusions.

One point stands out. If the multiplication factor per stage of the electron multiplier can be increased to say five per stage, the usefulness of the multiplier would be increased considerably. Such a factor does not appear to be impossible in view of the results of Mathes and Gilles. It seems very probable that the BeCu alloy used by them had some additional impurity that the American product does not have. It may be that some other type of activation will give better results. (D-3, P-4) Further investigation along this line is planned.

Reducing the time of assembly after activation should improve the multiplication. It is planned to drill on the method of assembly before heat treating and assembling the first tube in order to reduce the assembly time.

Dr. Allen has determined the efficiency of one of his tubes as a Beta ray detector (A-7) for electrons up to six kilovolts energy. The results are shown in Figs. 20, 21, and 22. The accuracy of his measurements were plus or minus 10%. The improvement in efficiency for twice the original gain is interesting and bears out the need for working on improvement of multiplication per stage. Allen predicts, on the basis of Trump and Van de Graaff's work(T-1), that the efficiency will drop to 10 to 20% for higher energies. The writer does not believe that it will go that low for the reason that Trump's data is taken for electrons with angle of incidence 0°, whereas in the multiplier the angle

of incidence is about 70°. If the specular effect holds at these lower energies, not only will there be a larger percentage of secondaries than predicted but most of the primaries that are elastically reflected will pass on to the next stage where they will have another opportunity to lose energy or knock out secondaries and so on. Therefore, the efficiency will not necessarily be low but the size of pulses will vary over a much wider range than the pulses for lower energy electrons.

T. Wimmet of the Synchrotron Laboratory has investigated the characteristics of Dare and Bowen's amplifier and has given an adverse report. If the amplifier should prove unsuitable, the type 10[illegible] (RLE designation) which Hahn has used successfully will be investigated as well as the circuit used by Allen (A-7).

It is anticipated that one of the major difficulties in the determination of multiplier efficiency will be the measurement of small current. The percentage accuracy will, however, largely depend on the number of electrons that are reflected back out the window. The method proposed for measuring these electrons lost should be accurate to 10%. Therefore, if the percentage of reflected electrons should be say 20% by measurement, the total accuracy of measurement will be on the order of 2% for the particular energy under consideration. The percentage of reflected electrons should be greatest for the energies from 3,000 to 20,000 volts and in this region the accuracy of measurement will, therefore, be lowest.

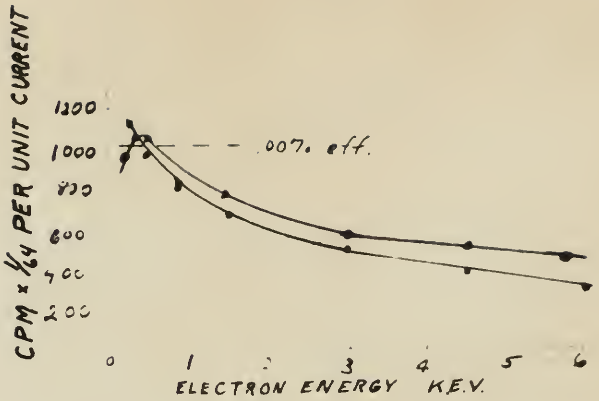


Fig. 20 Efficiency of a Multiplier as an electron counter. Gain for Upper curve twice that for lower. From Allen.

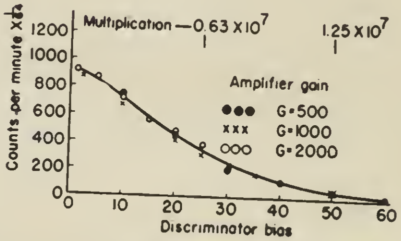


FIG 21. Counting rate as a function of the average voltage per stage of a 13-electrode multiplier tube. Energy of the electrons entering the tube is 900 volts

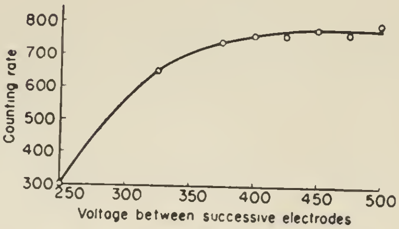


FIG 22 Discriminator bias curve for 500-volt electrons. A counting rate of 900 × 64 counts per minute represents 100% efficiency of detection

Part II

ABSTRACT

Two electron multipliers were built. The first included all the design changes proposed in Part One of this report. However, it was found that the design was far from satisfactory for eliminating corona. A second multiplier was built with further modifications to attempt to eliminate the difficulties. A preliminary test indicated that although this multiplier was less noisy than the first, the noise was still intolerably high. Circumstances did not permit further investigation or work on the project but it is probable that the noise emanated from corona discharge in the preamplifier.

PART II

The Efficiency of an Electron Multiplier Tube

The purpose of and the problems involved in the determination of the efficiency of an electron multiplier have been set forth in Part I of this report, which was submitted in September 1948 before very much experimental work was done.

An Allen tube was built but the design was modified with these considerations in mind:

(1) The first dynode would be at ground potential while the last was at about 4500 volts positive.

(2) In order to reduce the possibility of corona, the resistors between stages forming the voltage divider were placed inside the electron multiplier where they would be in the vacuum.

(3) Since the multiplier was also to be used as a Faraday Cage, it was considered necessary to bring out a lead for each dynode so that they could all be shorted together to permit the electrons collected on the dynodes to be measured along with those collected on the cage walls.

(4) A ready made Stupakoff eyelet of approximately the same dimensions as the Dare and Rowen specially constructed eyelets were used in the assembly.

(5) Since Dare and Rowen had considerable difficulty with vacuum leaks around their eyelets, the eyelets were mounted from the outside of the baseplate rather than the inside.

(6) The size of the flange at the base of the shell was increased to permit drilling an additional row of holes for bolting the multiplier to the beta ray spectrograph.

(7) To reduce the pumping time, the size of the tubing at the base of the multiplier was increased from one half inch to one inch.

The machining was done in the Nuclear Science and Engineering Laboratories machine shop.

It was originally planned to use Micalex for the supporting plates as Dare and Rowen had done, but the machine shop reported extreme difficulty in drilling the material. Consequently it was decided to change to mica, which was known to have worked successfully for W. E. Wright and T. M. Hahn, Jr.

In order to cut down the time the dynodes were to be exposed to the atmosphere between heat treatment and the time they actually were put under vacuum, the time of assembly of the dynodes in the supporting plates was reduced from 30 minutes to 5 by drilling in the procedure. It was found that two cm. of the extending nickel wire was the optimum length for assembling quickly. Having all the wires cut to the same length and two centimeters long, was a considerable factor in speeding up the assembly.

While the parts for the multiplier were being machined a preamplifier was built for coupling to the high voltage output lead of the electron multiplier.

It was small and compact and designed for mounting directly below the electron multiplier. It was modified from a design by T. Wimett for use with a photomultiplier. See fig. 23.

The characteristics of this preamplifier along with the amplifier unit built by Dare and Rowen were examined. Fig. 24 shows the response

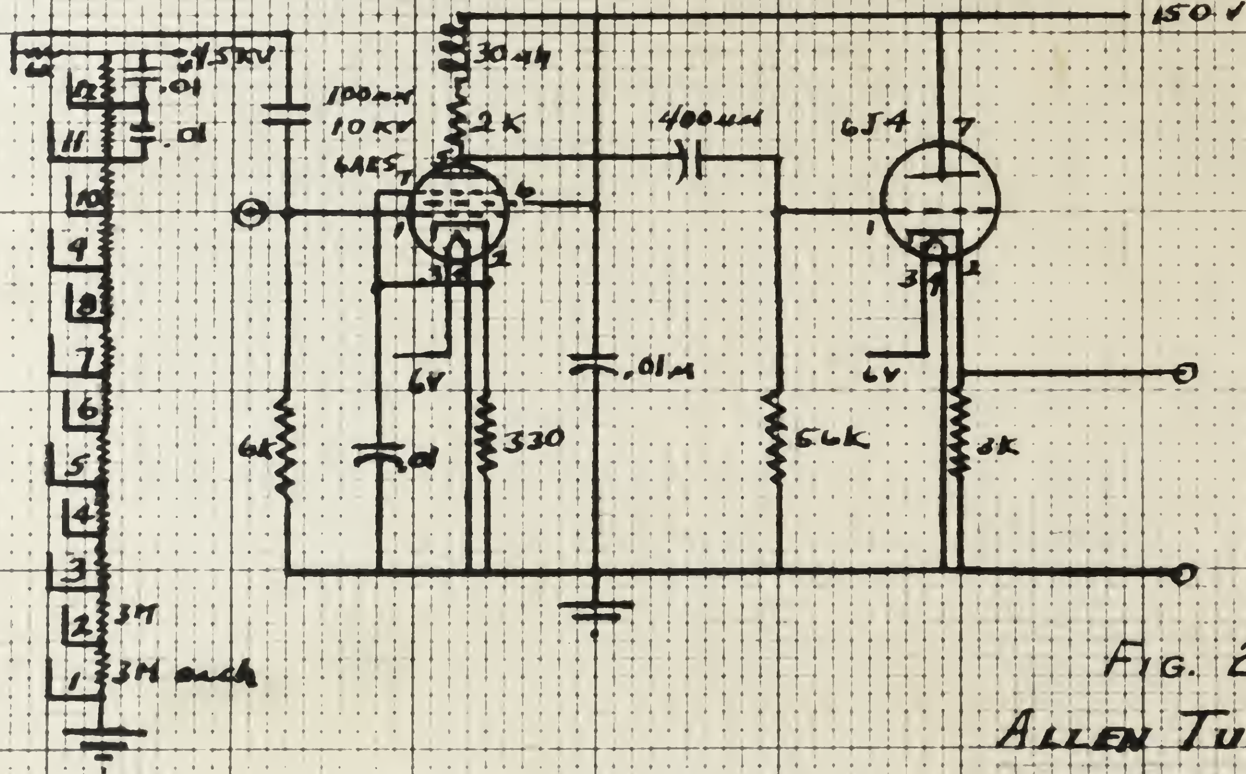
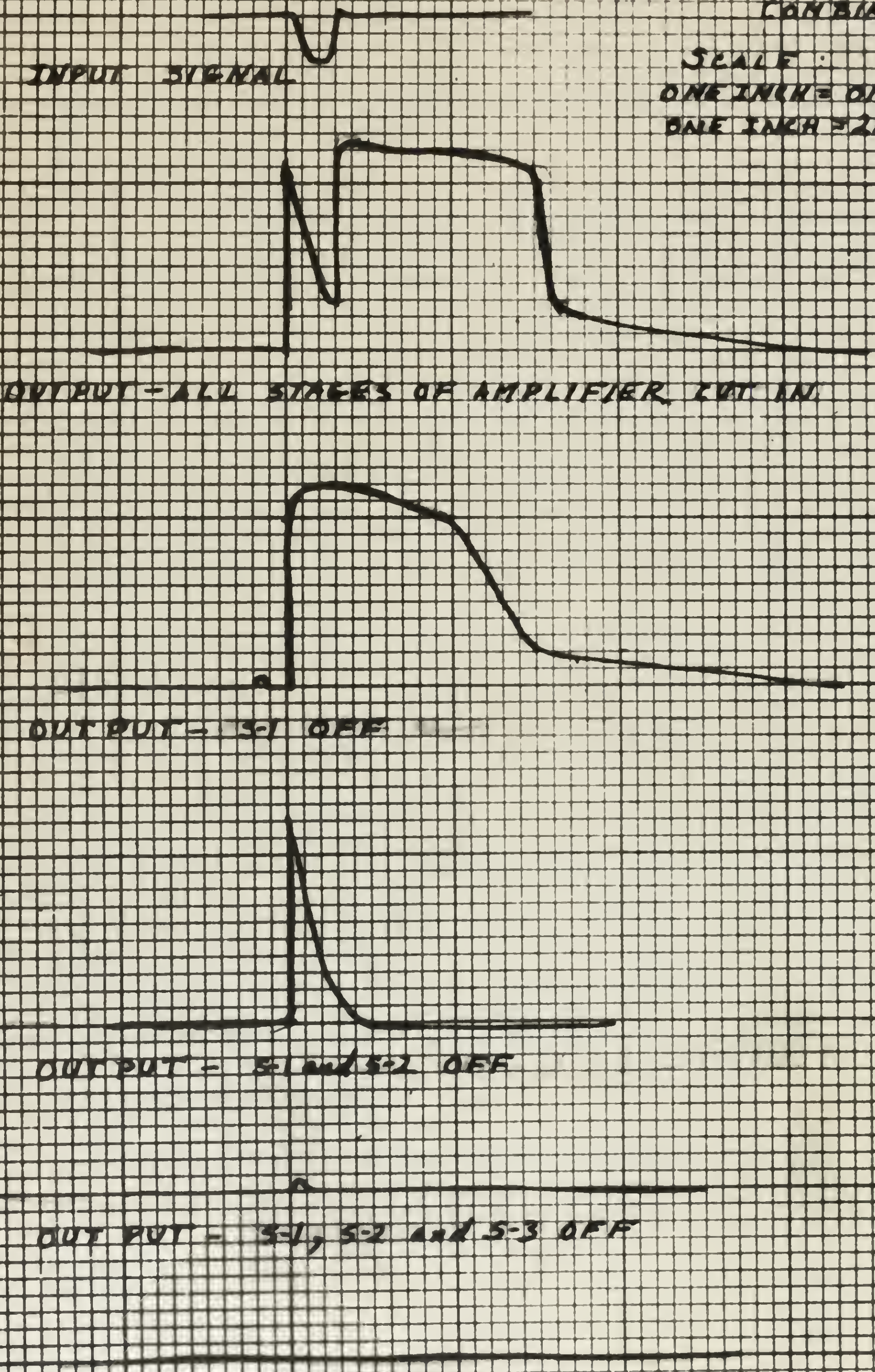


FIG. 23

ALLEN TUBE WIRING
DIAGRAM AND
TWO STAGE PREAMPLIFIER
ADAPTED FROM A DESIGN
BY T. WIMETT

FIG. 24
RESPONSE OF
TWO STAGE PREAMPLIFIER
AND DARE-ROWEN AMPLIFIER
COMBINATION

SCALE:
ONE INCH = ONE MICROSECOND
ONE INCH = 25 VOLTS



of the combination with a given signal. The preamplifier alone was found to have a gain of three.

It is evident that with even two of the stages of the Dare Rowen amplifier cut out the amplifier is overloaded with an input pulse of seven volts amplitude.

It appears that when the amplifier is overloaded very much it acts like a blocking oscillator. This is a serious drawback particularly when a scaler with a fast resolving time such as the G. E. Decade scaler is used, since it will count pulses such as that of fig. 24b as two pulses. A ringing of large amplitude gives additional pulses to the scaler which is sensitive to pulses greater than ten volts in amplitude and has a resolving time of about 10^{-7} seconds. However, since it is doubtful that the largest pulses from the electron multiplier exceed one volt, there would be little "over-pulsing" with one of the stages cut out. Data was taken in an attempt to ascertain whether or not Dare and Rowen's Allen tube was generating pulses of such large amplitude that triple and quadruple pulses were being generated where only one should be recorded. Appendix D shows the table of data taken in a series of ten one minute runs. The number of single, double, triple, and quadruple pulses registered in each minute period while observing the background count of the Dare Rowen Allen tube is recorded.

The data was first treated as though each multiple pulse was actually a single pulse and the "Chi test" for randomicity applied (See E-4). Next the data was treated so that the multiple pulses counted as so many single pulses. The results from the first test were such that the data may be considered satisfactory in terms of randomicity if the

multiple pulses are considered as singles, that is, the value of 0.85 for P is well within the limits of 0.02 and 0.98. But by the second treatment much better results were obtained since the value of P comes out .54 which is close to the optimum of .50. Thus in all probability there was no overloading of the Dare Rowen Amplifier by the Allen tube.

As mentioned in Part I of this report, it is essential that a scaler of fast resolving time be used when comparing the number of output counts with the input current, since it is desirable to be able to measure a current of 10^{-15} amperes with an accuracy of ± 4%. A standard Schmidt type scale of sixty four was built in the Nuclear Science and Engineering Electronic shop to be used in series with the General Electric decade scaler. Since the G. E. is a scale of 100, when the two are combined there is a total scale down of 6400 to one. Since the Schmidt scaler is not quite as fast as the G. E. it was placed after the G. E. scaler.

The Allen tube is a type I counter (E-4). That is, it is not deadened to a succeeding impulse while one pulse is in the process of being recorded. A current of 10^{-15} amperes would give us a true counting rate of about 5000 counts per second. Taking the resolving time as 2×10^{-7} seconds, the actual counting rate will be

$n = Ne^{-N}$ where N is true counting rate
T is resolving time

for N $n = N(1-N \quad) = 5000\ (1-5000 \times 2 \times 10^{-7}) = 5000\ (1 - 10^{-3})$

or there will be a statistical error of 1/10 of one per cent between the actual counting rate and the true counting rate. This is negligible compared to the error of three or four per cent expected in the input current measurement to be made by the Compton electrometer.

Originally it was planned to measure the input current with a balanced DuBridge circuit. However, on the advice of Professor Nottingham, who also offered to lend the necessary equipment, it was planned to change to a Compton electrometer as a measuring device. Professor Nottingham pointed out that although the DuBridge circuit provides for stabilizing for variations in supply voltage and so forth, actually the FP-54s themselves are more unstable than the items the circuit was designed to stabilize.

The eyelets were mounted in the base of the electron multiplier by a glassblower in R.L.E. glass blower shop, who heated it in an oven, applied the soft solder and dropped in the eyelets. Three eyelets had to be replaced due to cracks developing in the glass. When the base and tube shell were assembled, a small leak around one of the eyelets was found but it was easily stopped with a daub of glyptal.

The beryllium copper dynodes were sanded with three grades of fine sandpaper and were degreased before hydrogen firing. They were hydrogen fired at 600° C. for ten minutes. From the time of completion of the firing until the dynodes were assembled in the sideplates, all joints soldered and cleaned, and the assembly placed under vacuum,one hour and fifteen minutes elapsed. Pressure dropped slowly over the next twenty-four hours to 10^{-5} mm of mercury. It was allowed to remain over the weekend after which pressure had dropped to 2.4×10^{-6} mm of mercury.

When voltage was applied the pressure rose to about 10^{-5} mm and gradually dropped again.

The Dare Rowen amplifier was set with all stages cut in and with the biases P-1 and P-2 set at 3.5 volts and 5.5 volts respectively. The output of the Dare Rowen amplifier was lead to the first stage of the

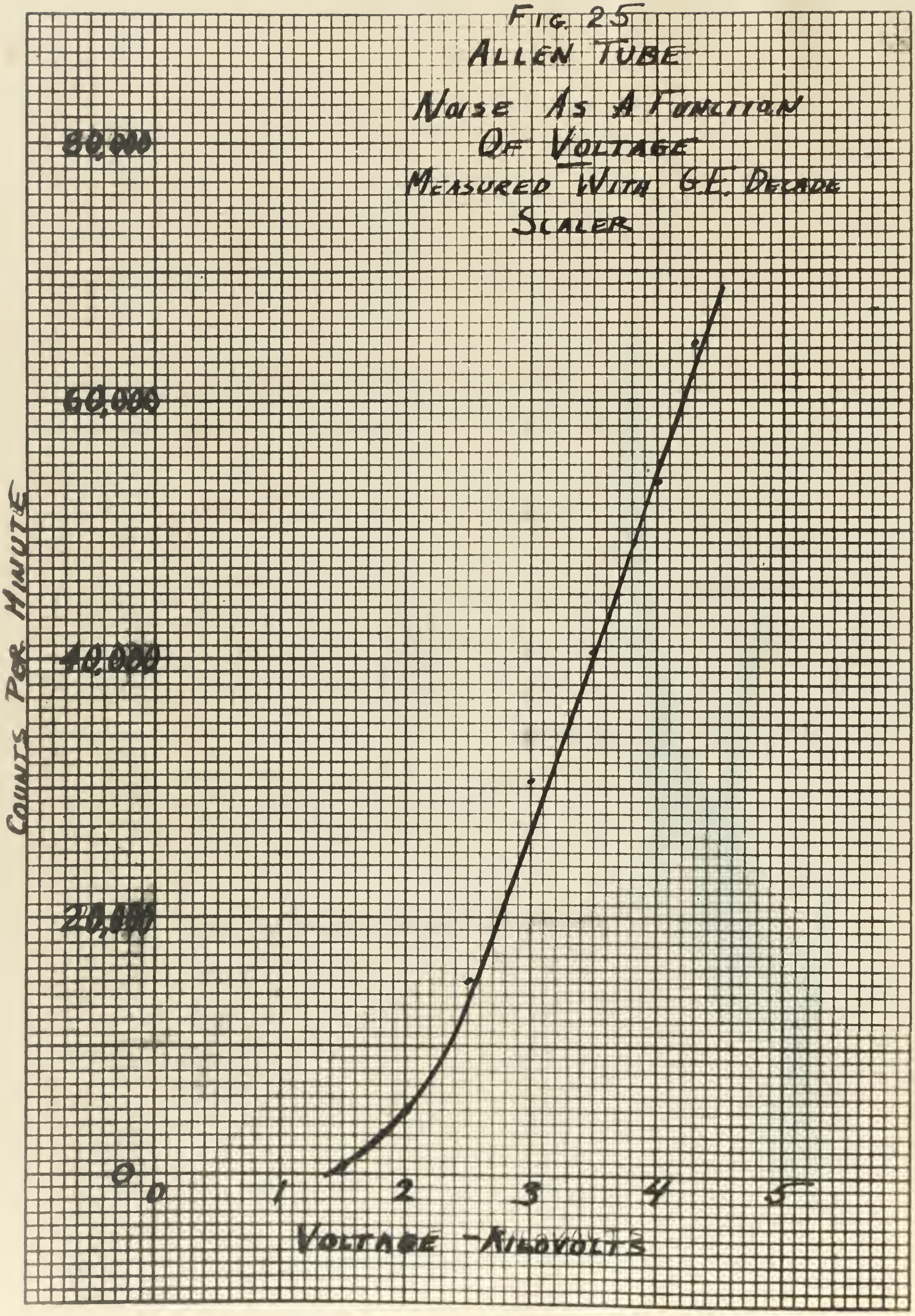


FIG. 25

ALLEN TUBE

NOISE AS A FUNCTION
OF VOLTAGE
MEASURED WITH G.E. DECADE
SCALER

decade scaler and the decade scaler set for 100-1 reduction; its output was fed into the Schmidt scaler.

A background count of anywhere from 30,000 counts to 60,000 counts per minute resulted for 4,200 volts on the multiplier.

Fig. 25 is a typical curve of the noise as a function of voltage.

Several weeks were spent in attempting to track down and reduce the noise sources. Considerable noise developed even with no voltage on the multiplier.

Also, Dr. Getting pointed out at this time that there was a basic fault in the construction of the multiplier, in that there was no resistor independent of the power supply condenser across which the signal could be developed. Correcting this entailed the labor involved in installing the six kilohm resistor shown in fig. 23 between the 4.5 Kv power supply and the collector electrode.

On the assumption that the noise was due to corona, the glass eyelets and the base plate were thoroughly cleaned with acetone, then Ceresin wax was painted on with a brush.

The dynodes were removed from the multiplier, the solder was cleaned off all joints and the entire assembly including the mica plates were degreased and again hydrogen fired to 650° C. for ten minutes.

After assembly and pumping down, the voltage was applied again and the background rate was found to still be extremely high.

On the assumption now that the noise was perhaps due to causes other than corona, other possible sources were investigated.

Eventually, at different times, all of the following were found

to cause background noise:

(1) Noisy preamplifier tube

(2) Bad coax cable from preamp to amplifier

(3) Preamp case not grounded properly

(4) Input to preamp not shielded

(5) Input shield not grounded

(6) Poor connections in preamp

(7) Poor connection between preamp and multiplier

(8) Poor connections in electron multiplier

(9) Poorly regulated power supply

Even after correcting all these faults, when the voltage was put on the electron multiplier the background count was still large.

With the failure of all attempts to eliminate noise in this electron multiplier, a modified design was sought which would further eliminate corona. A base plate was designed and machined which had instead of the previous 13 openings for eyelets only four. These four were arranged to provide the support for the dynode assembly. Only two of the regular Stupakoff eyelets were used; two two-inch glass insulators were used in place of eyelets for the high voltage terminals.

With this construction there is no provision for shorting all the dynodes together, but it is believed unnecessary to be able to do so. The multiplier may be considered a series of condenser plates with resistors between. The capacity between plates is estimated to be about 100 micromicrofarads. Since the resistance between the plates is three megohms the time constant will be 300 microseconds or with a reasonably steady influx of charged particles the system should come to equilibrium in one or two milliseconds permitting true input current to be measured practically

immediately. This does not take into consideration the capacity between the dynodes and the shell, but the effect of that capacitance can largely be eliminated by connecting the last dynode to the first and the shell.

This modified electron multiplier was found to be noisy also, but only about half as noisy as the previous one. There was no opportunity to conduct further experimentation, but it is believed that most of this noise could be reduced by rearranging the preamplifier so that the high voltage connections between the preamplifier and electron multiplier are reduced to a minimum. For example, the coupling condenser might be mounted directly on the electron multiplier base.

Fig. 26 is a photograph showing the arrangement of the equipment.

Acknowledgement and thanks are due to just about everybody in the Synchrotron Laboratory. All have assisted in one way or another with the project.

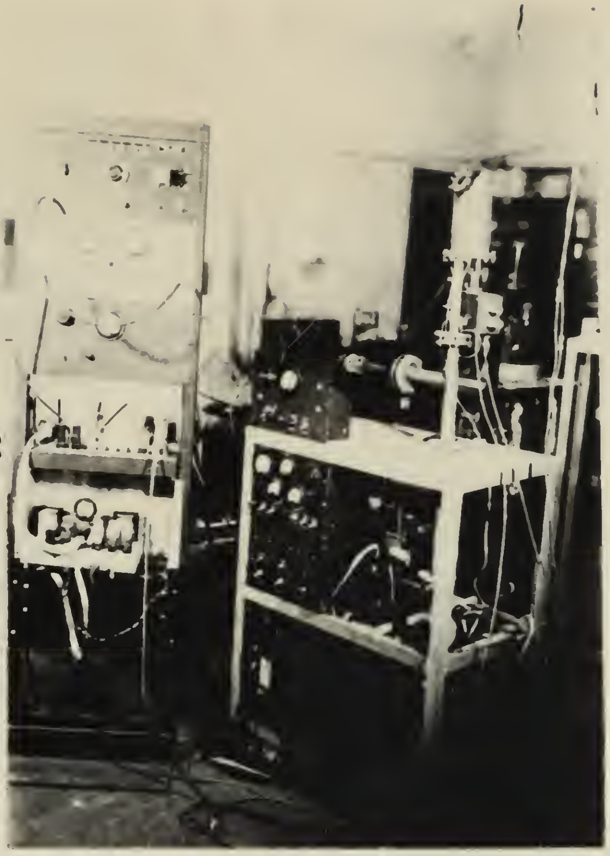


Fig. 26 - Assembled Equipment

Appendix D

Chi Test on Dare Rowen Electron Multiplier Data

Run	Single	Double	Triple	Quad.	Total	Multiple
1	5	1			6	7
2	2		1	1	6	9
3	1		1		2	4
4	1	1	2		6	9
5	4	1			5	6
6	1	1			2	3
7	4	1		1	6	10
8	2	2	1		5	9
9	2	2	1		5	9
10	2	1	1		4	7
					47	73
					4.7	7.3

Treating Multiple Pulses as Singles

X	$X-\overline{X}$	$(X-\overline{X})^2$
6	1.3	1.7
6	1.3	1.7
2	-2.7	7.3
6	1.3	1.7
5	.3	.1
2	-2.7	7.3
6	1.3	1.7
5	.3	.1
5	.3	.1
4	-.7	.5
		22.2

$Q^2 = \frac{22.2}{47} = .47$ $\quad nQ^2 = 4.7$

F = 10-1 = 9 from graph P = $\underline{\underline{.85}}$

Treating Multiple Pulses as Multiples

X	$X-\overline{X}$	$(X-\overline{X})^2$
7	-.3	.1
9	1.7	2.9
4	-3.3	10.9
9	1.7	2.9
6	-1.3	1.7
3	-4.3	18.5
10	2.7	7.3
9	1.7	2.9
9	1.7	2.9
7	-.3	.1
		50.2

$Q^2 = \frac{50.2}{73} = .69$ $\quad$ P = $\underline{\underline{.54}}$

$nQ^2 = 6.9 = X^2$ $\quad$ F = 9

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1	Secondary emission
2	Electron Multipliers
3	Small Curren Measurement
4	Electron Scattering
5	Electron Gun and Electron Beams
6	Power Supply
7	Counting Circuit Amplifiers and Scalers

U.S.N.A.P
89

Thesis 12612
C756 Costagliola
The efficiency of an electron multiplier tube.

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